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Estimating the Inverted Barometer Scale Factor for Altimetric Measurement Corrections

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ABSTRACT: Three years of TOPEX altimeter data and global sea-level pressure data from the ECMWF atmospheric general circulation model are used to assess the scale factor (of the inverted barometer (IB) approximation for static ocean response to atmospheric pressure. Two different methods, the **anomaly method** and the **collinear differences method**, are studied.

For each method two approaches are examined: the **pressure-only analysis** uses the TOPEX measured sea-level anomalies containing the pressure, wind, and steric signals; the **wind/steric-signal-removed analysis** uses Semtner's POCM_4B ocean model data in an effort to remove the wind-driven and steric ocean signals.

The anomaly and the collinear differences methods show identical results outside 20°S to 35°N latitude band, but show considerable differences inside this region. The collinear differences method yields more accurate results than the anomaly method in the tropics, with errors of less than 8 percent. Although using Semtner's POCM data introduces a new error source (model error), the benefit of isolating the ocean response to pressure signal from other signals outweighs the negative effect of the added error source.

As a result, the wind/steric-removed collinear differences method yields the most realistic values for the IB scale factor. Zonally, this best case yields an estimated α that is -8.8±2.2 mm/mb at the equator, is flat across the ±10° latitude band, has a mean value of -8.8 ±.8 mm/mb in the ±25° band, and a mean value of -9.4±0.5 mm/mb outside ±25° (within ±66°). The α obtained for the tropics is 20 to 30 percent closer to the

INTRODUCTION:

The issue of how the ocean surface responds to atmospheric pressure fluctuations is important for the study of ocean dynamics. However, since atmosphere-ocean interaction causes mass redistribution in the ocean, it indirectly affects the rotation rate of the earth [vanGysen et. al., 1995] as well as the polar motion of the earth [Dickman, 1988]. Moreover, mass redistribution introduces a time-varying component in the earth's gravitational potential field [Chao and Eanes, 1995; Dong et al., 1996]. Therefore, the ocean's response to atmospheric pressure fluctuations is important to geodesists as well.

Atmospheric pressure loading on the ocean surface was first discussed by R. Spitaler in his study of rotation of the earth in 1897. However, Jeffreys [1916] gave the subject a more thorough analytical treatment some 20 years later.

For the most part, sea level response to pressure loading has been approximated as an inverted barometer (IB), that is, sea level will rise (fall) approximately 1 cm for every 1 millibar decrease (increase) in atmospheric pressure [Wunsch, 1972; Gill & Niiler, 1973]. Although the IB approximation assumes only an isostatic response, pressure loading induces a dynamic ocean response as well. However, the magnitude of the current velocity generated by pressure loading is negligible compared with that generated by wind or thermohaline forcing [Maxgard, 1977; Philander, 1978; Tai, 1993; Ponte, 1993]. Moreover, the dynamic response diminishes as the pressure forcing frequency decreases [Tai, 1993]. Hence, regardless of the size of the dynamic response one should always remove the static inverted barometer sea level response in order to study the quasigeostrophic motions and dynamic response of the ocean to other forcing, including atmospheric loading itself [Tai, 1993].

Many studies have been carried out to assess the validity of the IB approximation. Some have used purely theoretical methods [Dickman, 1988; Tai, 1993], while others have applied atmospheric model output pressure and wind fields to numerical ocean models [Ponte et al., 1991; Ponte, 1992, 1993, 1994]. In addition, a number of studies have been done using either observed local sea level time series from tide gauge data [Wunsch, 1972; Bell and Goring, 1996], or globally observed altimetry data [vanDam and Wahr, 1993; Hoar and Wilson, 1994; Fu and Pihos, 1994; Gaspar and Ponte, 1996], or a combination of tide gauge and altimetry data [Wunsch, 1991]. While tide gauge studies are limited to the ocean areas adjacent to land masses, altimeter studies provide global coverage of the oceans. This study uses TOPEX altimeter data to investigate the validity of the scale factor (α) of the IB approximation in the open ocean.

DATA: January 1992 - December 1995

TOPEX Altimeter Data (Repeat Cycles 10-119)

- A modified version of the GDR edit criteria [Callahan, 1993] plus additional CSR edit criteria [Raofi, 1998] is applied
- The original GDR orbit is replaced with a 2 cm JGM-3 orbit solution computed at CSR [Ries and Tapley, 1999]
- GDR ocean tide solutions are replaced with the CSR 3.0 ocean tide model [Eanes and Bettadpur, 1990]

Atmosphere Pressure fields

- European Center for Medium-Range Weather Forecasts (ECMWF) uninitialized, mean sea-level pressure fields (1° by 1° by 6 hours) are used

Semtner's Parallel Ocean Circulation Model

- The POCM_4B model is used, forced by monthly averaged heat flux and ECMWF daily averaged wind fields; used to separate wind- and thermally-driven ocean signals from the total TOPEX-measured ocean signal

THE INVERTED BAROMETER MODEL:

The static ocean response (or sea-level adjustment) to atmospheric pressure variations is approximated as an inverted barometer, i.e.,

$$\eta_{IB} = -\frac{1}{\rho g}(P - \bar{P}) \qquad (1)$$

where η_{IB} is the IB adjustment in cm, ρ is the density of sea water in g/cm³, g is the acceleration of gravity in cm/s², P is the instantaneous pressure, and $\bar{P}$ is the mean pressure. Assuming ρ is never more than 1% different from the mean ocean water density [Gaspar and Ponte, 1996], 1/ρg is approximately 1 cm/mb. Therefore, Equation 1 says that a 1 mb change in barometric pressure will displace sea-level by one centimeter, hence leaving the combined water-air columnar weight unchanged. In other words, in regard to barometric pressure fluctuations, sea-level adjusts itself such that the ocean interior is shielded from surface pressure fluctuations. This statement generally holds for short to medium period fluctuations in barometric pressure.

MEAN PRESSURE:

Numerous studies have been performed to validate the theoretical 1 cm/mb static ocean response (IB scale). However, until very recently [Raofi, 1998; Dorandeu and Le Traon, 1999], there have been no explicit studies which discuss an appropriate model for $\bar{P}$ in Equation 1. Results of these and other recent studies agree that mean pressure variations need to be considered in the IB response model.

Figure 2 shows that mean sea-surface pressure is not constant in all latitudes and has a definite zonal structure. To remove the induced zonal bias, the correct $\bar{P}$ model should incorporate the local mean pressure. However, to remove the erroneously induced annual and semi-annual signals, this local mean pressure must be adjusted for temporal variations in the global mean sea-surface pressure.

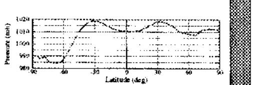

Figure 1: Zonally averaged ECMWF mean sea-surface pressure.

MEAN PRESSURE CONTINUED:

The $\bar{P}$ model proposed by Raofi [1998] and used for this study is defined by:

$$\bar{P} = \bar{P}(\phi,\lambda) + (\bar{P}_{full}(t) - <\bar{P}_{full}(t)>) \qquad (2)$$

and the IB correction at any point and time becomes

$$\eta(\phi,\lambda,t) = \alpha(P(\phi,\lambda,t) - [\bar{P}(\phi,\lambda) + (\bar{P}_{full}(t) - <\bar{P}_{full}(t)>)]) \qquad (3)$$

- Where the subscript "full" implies that every gridpoint of every pressure field has been used (as opposed to erroneously using only those pressure fields sampled by T/P) and the brackets < > denote the time-averaged mean global pressure.

THE IB SCALE FACTOR α:

The IB scale factor α is evaluated by applying the IB correction of Equation 3 to TOPEX sea level anomalies (SLA). The scale factor calculations are computed by two different methods, the **anomaly method** and the **collinear differences method** and are compared to the theoretical -10 mm/mb scale factor.

ESTIMATION:

- A least squares estimation method is used to regress the TOPEX SLA record versus ECMWF atmospheric model pressure records to estimate the IB scale α
- To reduce measurement noise, normal point averages representing 500 km groundtrack arc lengths are used in place of individual SLA measurements
- At any given location (φ,λ), all SLA measurements from all TOPEX cycles are used to simultaneously solve for α
- ECMWF pressure data are interpolated to SLA measurement locations to compute pressure normal points compatible to SLA normal points

METHODOLOGY:

1. The Anomaly Method (AM)

Regression model:

$$SLA_i = \alpha(P_i - \bar{p}) + \varepsilon_i \qquad (4)$$

2. The Collinear Differences Method (CDM)

Regression model:

$$SLA_i - SLA_{i+1} = \alpha(P_i - P_{i+1}) + \varepsilon_i \qquad (5)$$

- Where P is the instantaneous pressure, $\bar{P}$ is the mean pressure model described in Equation 2, "i" is the TOPEX repeat cycle number, and ε is the estimation error.

OCEAN SIGNALS IN SLA:

$$SLA^* = H_{orb} - h_{alt} \qquad (6)$$

- Where SLA* contains all ocean signals, H_{orb} is the orbit height, and h_{alt} is the altimeter measurement corrected for all instrument and media effects (including the sea state bias)

$$SLA^* = \eta_{tide} + \eta_{ster} + \eta_{wind} + \eta_{pres} + \varepsilon' \qquad (7)$$

- Where η_{tide} is the tide signal, η_{ster} is the steric signal, η_{wind} is the wind signal, η_{pres} is the pressure signal, and ε' is the sum of all measurement and model errors

RESULTS:

CASE A. REMOVING ONLY THE TIDE SIGNAL

$$SLA = SLA^* - \eta_{tide} \qquad (8)$$

- Ocean tide signals are removed using the CSR 3.0 ocean tide model (steric, wind, and pressure signals remain).

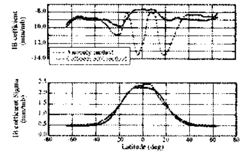

Figure 2: Estimated IB coefficient α (top) and its 1 σ error (bottom) for the Anomaly Method (AM) and Collinear Differences Method (CDM)

- Anomaly Method (AM). Both the SLA record and the pressure records contain the complete signal spectrum
- Collinear differences Method (CDM). The zero-frequency and low-frequency (periods longer than a few months) signals are eliminated from both sea level and pressure records
- Pressure variability in the tropics is small, 2 to 4 mb, in a root-mean-square (RMS) sense
- Low-frequency pressure variability in the tropics is less than 8 percent of the total pressure variability in this region and less than 10 percent of the total pressure variability elsewhere
- Low-frequency wind variability in the tropics is 4 to 5 m/s RMS
- Low-frequency wind variability in the tropics overwhelms pressure variability, leading to low signal to noise ratio in this region
- The behavior of the AM curve in the tropics may be related to the low-frequency variability in the equatorial currents (see Figure 3)

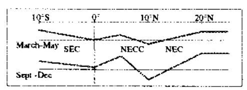

Figure 3: Diagram of dynamic ocean topography associated with Pacific equatorial currents, looking West [after Wyrtki, 1974, Fig. 10].

CASE A OBSERVATIONS:

- The AM regression results, particularly in the tropics, are corrupted by the strong wind-driven signal
- Removing the low-frequency signals (CDM) eliminates less than 10 percent of total pressure signal (in a root-sum-square (RSS) sense). CDM removes considerably more of the wind signal compared with the pressure signal
- Hence, the CDM regression results are at most 10 percent in error due to lack of complete pressure signal spectrum
- The large disagreement between the two methods in the tropics is primarily due to large errors in the AM regression results caused by large wind-driven to pressure-driven signal ratio
- The CDM regression solution is closer to the true ocean response to pressure variations than the AM solution

CASE B. REMOVE THE TIDE, STERIC, AND WIND SIGNALS

$$SLA = SLA^* - \eta_{tide} - \eta_{ster} - \eta_{wind} \qquad (9)$$

- Steric- and wind-driven signals are removed by subtracting Semtner's POCM SLA from the measured TOPEX SLA
- Ocean tide signals are removed using the CSR 3.0 tide model

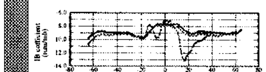

Figure 4: Zonally averaged IB Scale α for the collinear differences method (Case A = blue; Case B = green). Case B anomaly method (AM = red) is also plotted for comparison

- The steric signal is a seasonal (low-frequency) signal. Since the CDM has already eliminated low-frequency signals, removing the steric signal primarily affects the AM
- Wind and pressure have *opposing* effects on sea level, e.g., a low pressure cell causes the water to bulge up while the wind curl associated with the low pressure cell gradually pumps water away from the center of the pressure cell towards its perimeter (Ekman pumping)
- The sea-level response to pressure fluctuations is nearly instantaneous
- Sea-level response to wind variations (in the form of Ekman pumping) requires time to reach equilibrium. Response is faster near the equator and slower away from the equator [Fu and Pihos, 1994]
- The lower the frequency of a pressure signal, the more time its associated wind would have to negate the effect of the pressure response
- Wind effect does not completely cancel the effect of pressure but somewhat reduces its magnitude
- With the wind signal removed, one would expect the estimated IB scale to increase in magnitude (move closer to the theoretical -10 mm/mb value)

CASE B OBSERVATIONS:

- As expected, removing the wind signal moves the CDM IB scale curve about 0.5 mm/mb closer to the theoretical -10 mm/mb value (see Figure 4)
- Removing the wind signal has a slightly smaller effect inside the tropics compared with the outside, this is perhaps because there are more mid- to high-frequency wind signals outside the tropics
- The AM (Figure 4, red line) still has large errors in the tropics, particularly in the northern hemisphere. This suggests that Semtner's POCM does not completely recover the low-frequency wind signals in the tropics, especially in the region +10° to +30° North
- Even after removing the wind signal, the signal (pressure) to noise (wind, etc.) ratio remains low in the tropics
- Outside the tropics, both the AM and CDM give nearly identical results with a mean value of -9.40 mm/mb
- This suggests that outside the tropics, the ocean's response to pressure variations is nearly that of a perfect IB for the full range of frequencies (except those frequencies higher than once every 2 to 3 days [Ponte, 1991])

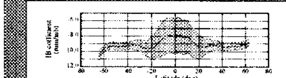

Figure 5: Zonally averaged value of estimated inverted barometer coefficient α for the wind- and steric-signals removed collinear differences method (CDM). The shaded area is the ±1σ error for α.

ERROR ANALYSIS:

- Errors in the estimated α can be divided into 5 categories due to: orbit error, altimeter range measurement error, model pressure error, correlation between pressure fluctuations and IB corrected SLA, and other miscellaneous errors
- Inside the tropics, the total root-sum-square (RSS) error (Table 1) agrees well with the formal estimation error (1-σ) shown in Figure 5
- Outside the tropics, the RSS error of 0.8 mm/mb suggests that the 1-σ estimation error of 0.54 mm/mb is optimistic

	ERROR (mm/mb)	
ERROR SOURCE	Tropics	Outside the Tropics
Pressure	0.4	[illegible]
Orbit	0.8	[illegible]
Range Measurement Correction		
Wet Troposphere	0.7	[illegible]
Sea-State Bias	0.8	0.5
Ionosphere	0.4	[illegible]
Ocean Tide	1.0	[illegible]
SLA	0.2	[illegible]
Residual Geoid	0.0	0.0
Removing Low-Freq. Signal	0.4	0.0
RSS Total	1.8	0.8

Table 1: Summary of error analysis for IB coefficient with individual error contributions and their RSS total [Raofi, 1998]

α SCALE FACTOR SUMMARY TABLE:

	tide signal removed	tide, wind, and steric signals removed
Anomaly Method		
Tropics	-10.71 ±1.71	-9.53 ±1.71
Poleward of ±30 degrees	-8.71 ±0.61	9.40 ±0.61
Global	9.82 ±1.23	-9.47 ±1.23
Collinear Diff. Method		
Tropics	-8.33 ±1.76	8.85 ±1.76
Poleward of ±30 degrees	8.93 ±0.54	-9.50 ±0.54
Global	-8.68 ±1.22	-8.96 ±1.22

Table 2: Summary results of the different methods and cases in the estimation of the IB coefficient. The red numbers indicate results for the best performing method. All results are in mm/mb.

SUMMARY AND CONCLUSIONS:

- Ocean models, such as Semtner's POCM_4B, can successfully (within model errors) be used for separating wind- and steric-signals from other signals in the ocean
- Unlike previous studies, the results of this study show that the estimated IB scale is flat across the equator (in the ±10° band)
- Inside the tropics, the estimated IB scale is 10 to 20 percent smaller in magnitude than the theoretical -10 mm/mb value; however, it is 20 to 30 percent closer to theoretical value as compared to two recent IB studies base on TOPEX/Poseidon data (see Figure 5)
- Outside the tropics, the estimated IB scale is nearly 95 percent of the theoretical value, supporting the validity of the IB approximation of the ocean's response to pressure variations
- Since the ocean's response to pressure variations describes a physical phenomenon, the significant deviations from a pure IB response inside the tropics are possibly due to: low signal to noise ratio, lack of ability to completely separate other signals from pressure-driven ones in the ocean, and range measurement and range correction errors
- Using a variable IB scale, or one which is different from the theoretical value, may mask other static or dynamic signals of interest in the ocean
- Hence, for satellite applications, it is recommended to use an IB model which uses the mean pressure model used in this study along with the theoretical -10 mm/mb IB scale factor α

References: see attached